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COMBUSTION MECHANISM OF PARTICLES OF ALUMINUM-MAGNESIUM ALLOYS

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А а	*А а*	A, a	Р р	*Р р*	R, r
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В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
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З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
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К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
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М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

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DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

COMBUSTION MECHANISM OF PARTICLES OF ALUMINUM-MAGNESIUM ALLOYS

Ye. I. Popov, L. Ya. Kashporov,
V. M. Mal'tsev, and A. L. Breyter
(Moscow)

Powders of aluminum-magnesium alloys possess higher reactivity than aluminum powders, which explains the advantage of using them. In order to assure effective burning of alloy powders we must know the mechanism and laws of the particle combustion process. Existing information on the combustion of the particles of aluminum-magnesium alloys is incomplete and contradictory.

Photographing burning alloy particles containing 50% magnesium [1] shows that combustion occurs in two stages: first, the magnesium burns rapidly forming a diffusive flame and destroys the particle, while the aluminum is dispersed in the form of fine particles, which continue to burn more slowly. The spectroscopic studies of [2] show that at the beginning of the process the combustion of the magnesium prevails, and that the fraction of burning aluminum increases as the magnesium is consumed. In the opinion of the authors of [3], the presence in the combustion products of double oxides, detected by X-ray diffraction analysis, is an indicator of possible vapor-phase combustion of the aluminum and magnesium in stages, since recombination of simple aluminum and magnesium oxides is not very probable. However, this argument is

not sufficiently convincing, since the vapors of both oxides taken individually must be unsaturated with respect to their pure liquids, and when the vapors are mixed the condensation of the liquid phase of the intermediate composition may begin, for which supersaturation is greater than one [4]. The double oxide $MgAl_2O_4$ may also be formed in the pre-flame surface oxidation which precedes vapor-phase combustion [5].

In the present work we have studied the combustion process of individual particles of aluminum-magnesium alloys under atmospheric pressure. The particles contained 5, 10, 20, 50, 70, 90, and 95% magnesium and were prepared in the form of spheres measuring from 100 to 600 μm. The studied particle was placed on the point of a tungsten needle and burned in air or in the flame of compressed mixtures of ammonium perchlorate and urotropine, which have calculated temperatures of 2500, 2700, and 3100°K. In the case of combustion in air the particles were ignited from a miniature Silit rod, heated by an electrical current. The combustion process was studied by mean of the "Konvas" and SKS-1 [CKC-1] movie cameras with magnification of up to ×10.

The photographs of burning particles enable us to establish the sequence and duration of the combustion stages and combustion peculiarities during the entire process. The most important combustion characteristic of aluminum-magnesium alloy particles is the two-stage nature of the process (Fig. 1a). In the first stage the particle is surrounded by an assembly of flames, which form a heterogeneous glowing zone of reaction products. If we compare the nature and dimensions of the glowing zone which surrounds the aluminum-magnesium alloy particle in the first combustion stage with the nature and dimensions of the glowing zone around the burning magnesium particle (Fig. 1b) and with the photographs and descriptions of the magnesium combustion process given by other authors [6-10], then we come to the conclusion that it is primarily the magnesium of the particle that burns in this stage.

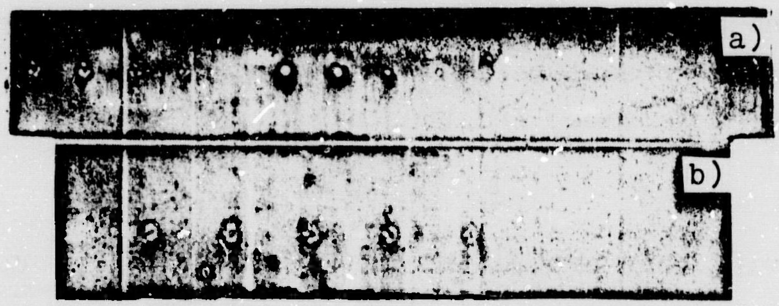

Figure 1. Combustion of metal particles in air. a) alloy of 30% aluminum +70% magnesium; b) magnesium.

The distinguishing features of the first combustion stage are the heterogeneity of the flame, which consists of individual flames, and the constant dimensions of the particle and the flame zone, which is maintained almost throughout the entire stage. The preservation of the constant particle dimensions and a constant flame zone leads us to believe that the liquid alloy drop is encased within a hard oxide shell, which forms as a result of the oxidation which preceded ignition and occurred in conjunction with the surface mechanism. This also excludes the possibility that the controlling stage of the process is the diffusion of magnesium from the drop to its surface, since in this case the glowing zone should decrease in time. The heterogeneity of the flame zone implies that the oxide film is also heterogeneous. The magnesium leaks through the defects in the oxide layer (cracks, pores), and this causes it to interact with the air oxygen in the flames of the vapor-phase diffusion flame.

The low degree of diffusion resistance of the oxide film on the aluminum-magnesium alloy particles is explained by the fact that magnesium oxide, which has low protective property, prevails in the film [3, 11, 12]. At the end of the first combustion stage the intensity of the glow decreases sharply. This confirms the fact that no substantial burning of aluminum occurs during the time of the first stage. However, during this time, when the burn-up of magnesium is complete, there is an increase in heterogeneous reactions, as is evident by the appearance of brightly glowing

centers on the particle surface. The heat which is liberated during the heterogeneous reactions heats the particles to the melting temperature of the oxide, and thus begins the second stage of combustion.

The glowing zone around the particle in the second stage of combustion is homogeneous, brighter and smaller in size as the metal is consumed. The homogeneity and sphericity in the flame zone indicate that the oxide film on the particle surface is homogeneous and, apparently, is molten. The diffusion of the metal through the stem occurs because of the low diffusion resistance of the liquid oxide. It is also possible that in this combustion stage there is no oxide film on the surface of the particle, as assumed in [13], where the combustion of aluminum was studied. The size of the flame zone considerably exceeds that of the particle, and this indicates that the metal burns in the vapor phase. If we compare the nature of the second combustion stage with the well known combustion pattern of aluminum [1, 7-10, 13, 14], then we see a great similarity, which confirms combustion of the aluminum in this stage of the process.

As the metal is consumed the dimensions of the flame decrease and, consequently, the dimensions of the burning drop, since the oxide shell continues in the molten state.

The two-stage continuous combustion nature is inherent in aluminum-magnesium alloys burning in air when they contain no less than 30% magnesium. If the concentration of magnesium is lower, the two-stage process becomes shorter. Here the nature of both stages remain unchanged, but the trans tion from the first to the second stage occurs differently. In this case the glowing zone at the end of the first stage decreases to the size of the particle itself, the process of vapor-phase combustion ceases, and the aluminum is burned up only after the particle has been reignited.

Particles which do not reignite are the hollow, porous oxide shells contained inside the drop of unburned aluminum.

Thus, the change in the dimensions of the glowing zone in time is complex. Figure 2 shows the value of the ratio of the radius of the glowing zone r_c to the initial radius of the particle r_0 for alloys burning in conjunction with a two-stage continuous mechanism during the entire combustion process (relative combustion time θ lies along x-axis). When the particle ignites quantity r_c/r_0 quickly reaches its maximal value (section ab). Then, for most of the duration of the first combustion stage ratio r_c/r_0 remains constant (section bc), and then decreases, passing through the minimum at point d. Further, as the second stage begins, this ratio increases somewhat (section de), and, finally, it decreases monotonically to the final value (section ef). For alloys containing less than 30% magnesium the nature of the evolution in ratio r_c/r_0, shown in Fig. 2, is generally preserved, although the moment of transition from one stage to the other becomes significantly indeterminate.

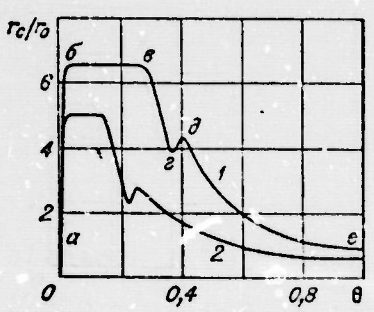

Figure 2. Time dependence of ratio of radius of glowing zone of particle to radius of original particle. 1 - alloy of 30% aluminum +70% magnesium; 2 - alloy of 50% aluminum +50% magnesium.

As we see in Fig. 2, property r_c/r_0 increases with an increase in the concentration of magnesium in the alloy. This shows that the staged nature of the combustion process cannot be explained by the encapsulation of the aluminum by the magnesium, which would assume the limited mutual solubility of the alloy components. In this case the value of the ratio should not depend on the relationship of the components.

If we compare curves 1 and 2 of Fig. 2, then we should also find in Fig. 3 that when the alloy is magnesium enriched the duration of the first stage of the combustion process increases. This dependence is practically the same for particles of all studied dimensions, which can be explained by the following reasoning.

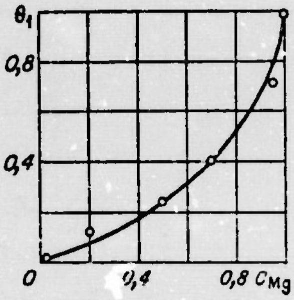

Figure 3. Relative length of first combustion stage as a function of the composition of aluminum-magnesium alloys.

The total combustion time of the alloy particle τ is composed of the combustion time of magnesium τ_1 and the combustion time of aluminum τ_2. According to most experimental data, the combustion time of magnesium particles is proportional to the diameter of the particle to the 2.0 power, on the average [9, 15, 16], the combustion time of aluminum particles - to the 1.8 power [9, 13, 17-20]. Then

$$\theta = \frac{\tau_1}{\tau_1 + \tau_2} \frac{k_1 (d_0^2 - d^2)}{k_1 (d_0^2 - d^2) + k_2 d^{1.8}},$$

where d_0 is the initial diameter of the particle; d - particle diameter before beginning of second stage; k_1 and k_2 - coefficients of proportionality. Quantities d_0 and d are related by

$$\frac{d_0}{d} = \sqrt[3]{\frac{x}{1-x} \cdot \frac{\rho_2}{\rho_1} + 1},$$

where x is the magnesium in the alloy; ρ_1 and ρ_2 - density of magnesium and aluminum, respectively. Quantities x, ρ_1 and ρ_2

are constant for each alloy, and thus $d=kd_0$. Then

$$\theta = \frac{k_1(1-k^2)}{k_1(1-k^2)+k_2k^{1.8}d_0^{-0.2}},$$

from which it is apparent that the relative burn-up time of the magnesium in an alloy particle burning according to the two-stage mechanism should have an extremely weak dependence on the initial diameter of the particle, which has also been proven experimentally.

The combustion process of the alloy particles depends essentially on the characteristics of the surrounding medium. Combustion in oxidizing mediums, created by the hot mixtures of ammonium perchlorate and urotropine, occurs, as a rule, with an explosion (fragmentation). The presence of an explosion is characteristic for particles of all compositions (Fig. 4). As a result of explosion a glowing zone of considerable dimensions is formed, an indicator of prevailing vapor-phase combustion. The photographs of the burning particles prior to fragmentation (Fig. 5) show that heterogeneous reactions occur on the entire surface of the oxide shell. The heat of the heterogeneous reactions causes intensive evaporation of the metal, breaking the oxide shell and spraying the unevaporated drop. In the opinion of the author of [21] fragmentation of aluminum-magnesium alloy particles is caused by the very great difference between the boiling temperatures of magnesium and aluminum, as a result of with the boiling of the magnesium when the particle is in the high-temperature zone has an explosive nature and leads to fragmentation of the remaining aluminum.

Fragmentation of the particles occurs in all three flames (Fig. 6), and, consequently, even at a temperature of 2500°K conditions favorable to the explosion combustion process are created. This is only natural, since this temperature exceeds the boiling temperature of both components.

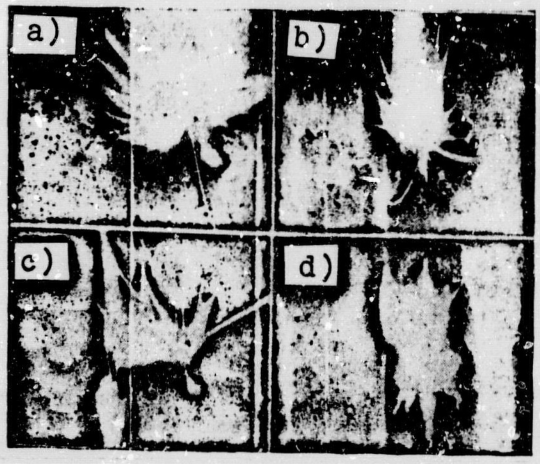

Figure 4

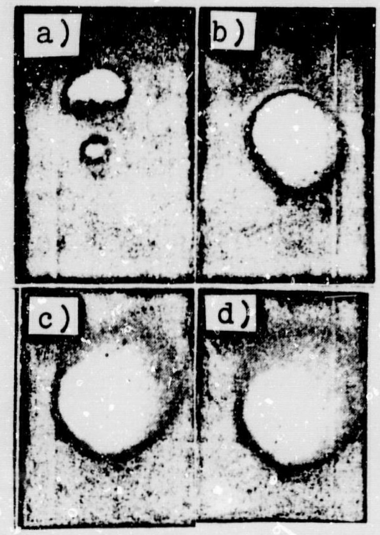

Figure 5

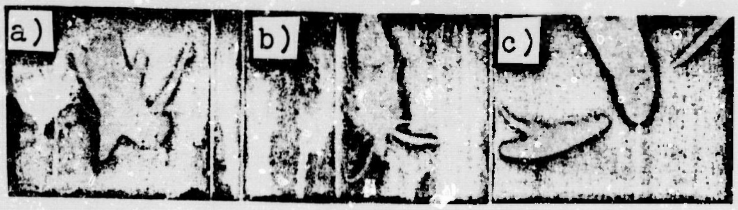

Figure 6

Figure 4. Fragmentation of metal particles in oxidizing flame (temperature 2700°K). a) aluminum; b) alloy of 95% aluminum +5% magnesium; c) alloy of 90% aluminum +10% magnesium; d) alloy of 80% aluminum +20% magnesium.

Figure 5. Initial combustion stage of particle of alloy containing 95% aluminum +5% magnesium in oxidizing flame (temperature 2700°K).

Figure 6. Fragmentation of particles of alloy consisting of 95% aluminum +5% magnesium in oxidizing flames at different temperatures, °K. a) 2500; b) 2700; c) 3100.

This study brings us to the following conclusions:

1. The combustion of particles of aluminum-magnesium alloys in air occurs in two stages; in the first stage it is primarily magnesium that is burned, in the second - aluminum. When the alloy contains no less than 30% aluminum the combustion process is continued; if it contains less a break develops between the stages.

2. The combustion of both magnesium and aluminum occurs primarily in the vapor-phase. When magnesium is burned the oxide shell on the particle is solid, but not dense, and the magnesium is diffused through defects in the film, thus leading to the

formation of a heterogeneous flame consisting of individual flames; the size of the glowing zone does not change during the course of this stage. When aluminum is burned the oxide film is in the liquid state or is absent, and the flame is spherical and homogeneous; the size of the combustion zone decreases as the particle is burned.

3. When the concentration of magnesium in the alloy is high the size of the stationary combustion zone and the length of the first stage of the combustion process increase.

4. When the ambient temperature increases combustion is accompanied by fragmentation of the aluminum-magnesium alloy particles.

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